CHAPTER 3

ANALYSIS OF THE INTERIOR PERMANENT MAGNET MACHINE FEEDING AN IMPEDANCE LOAD

3.1 Introduction

In this chapter, the IPM generator feeding an impedance load for the case when a shunt capacitor is present at the terminals, and also when the shunt capacitor is absent will be presented. A diagram of the topology is shown in Figure 3.1.

First, a general mathematical model of the IPM feeding an RL load will be developed using the dq synchronous reference frame transformation. The result of this derivation gives an eighth order equation. Then, the case when only a resistive load is fed by the IPM generator with shunt capacitor compensation will be examined. A fourth order equation is developed to describe the system. The final configuration, the IPM generator feeding a resistive load, will be examined and the mathematical model developed to describe the system results in a fourth order equation; however, it will be shown that the fourth order equation for this system can, in fact, be reduced to a simple quadratic equation by combining the stator resistance of the machine with the load resistance.

The comparison between experimental results and predicted results for the cases of a resistive load with and without shunt capacitor compensation will be made and the resulting graphs will be presented and commented on. The measured waveforms of the IPM feeding a resistive load will also be given in this chapter.

3.2 Mathematical Model for IPM Feeding an RLC Load

Figure 3.2 shows a schematic diagram of the IPM machine connected to an impedance load with shunt capacitors connected at the terminals of the machine. As shown in Chapter 2, the voltage Equations for the IPM machine are [31]

$$\begin{aligned} v_{qs} &= r_s\, i_{qs} + p\, \lambda_{qs} + \omega\, \lambda_{ds} \\ v_{ds} &= r_s\, i_{ds} + p\, \lambda_{ds} - \omega\, \lambda_{qs} \ , \end{aligned} \tag{3.1}$$

where

$$p = \frac{d}{dt} \ .$$

The voltage equations for the inductor in the dq reference frame are

$$\begin{aligned} v_{iqs} &= \omega L\, i_{dr} + p\, L\, i_{qr} \\ v_{ids} &= -\, \omega L\, i_{qr} + p\, L\, i_{dr} \ . \end{aligned} \tag{3.2}$$

Also, the total voltage across the load is given as

$$\begin{aligned} v_{qs} &= v_{iqs} + i_{qr}\, R_L \\ v_{ds} &= v_{ids} + i_{dr}\, R_L \ . \end{aligned} \tag{3.3}$$

The current equations for the capacitor are

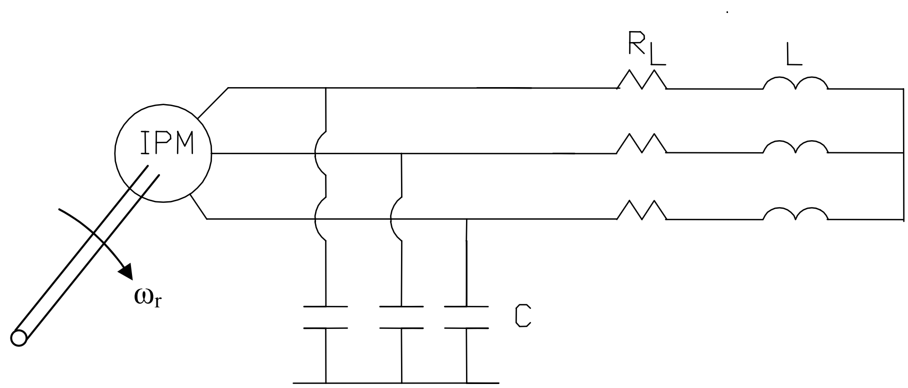


Figure 3.1. IPM generator feeding an RL impedance load with capacitive compensation

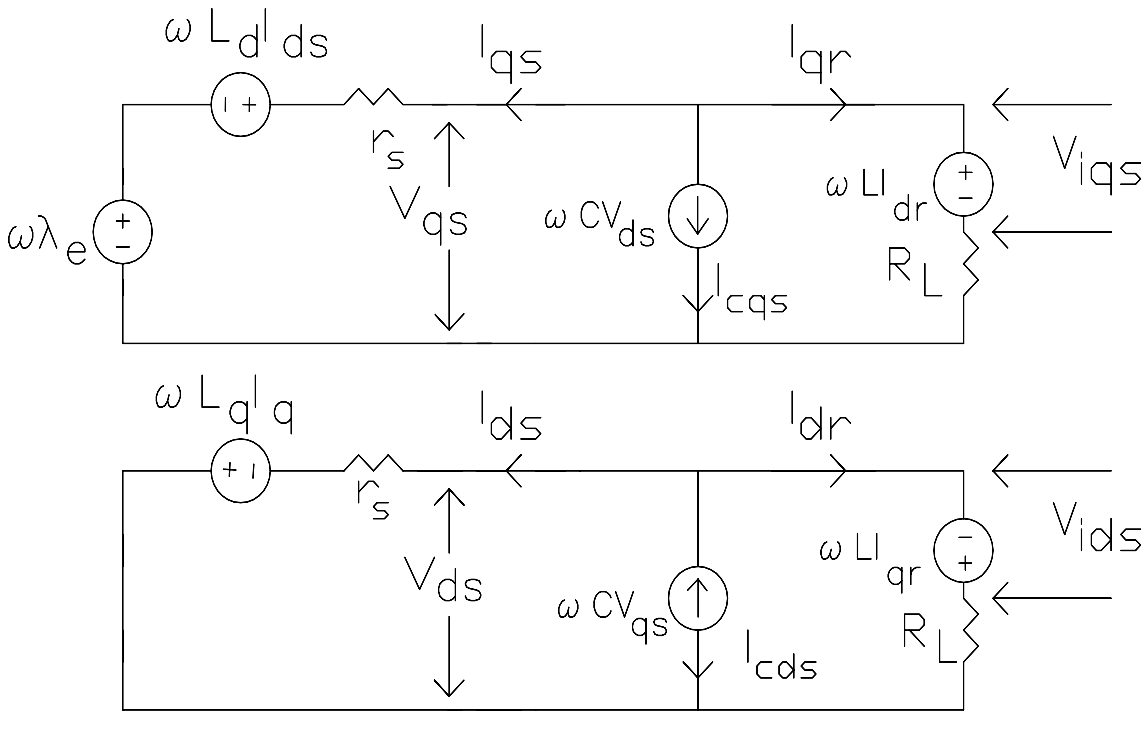


Figure 3.2. DQ equivalent circuit of IPM machine connected to an RLC load

$$i_{cqs} = \omega C\, v_{ds} + p\, C\, v_{qs}$$
$$i_{cds} = -\,\omega C\, v_{qs} + p\, C\, v_{ds} \; . \qquad (3.4)$$

The equations given in Equations 3.1, 3.2, and3.4, at steady state, become, respectively,

$$V_{qs} = r_s\, I_{qs} + \omega\, \lambda_e + \omega\, L_d\, I_{ds}$$
$$V_{ds} = r_s\, I_{ds} - \omega\, L_q\, I_q \; , \qquad (3.5)$$

$$V_{iqs} = \omega L\, I_{dr}$$
$$V_{ids} = -\,\omega L\, I_{qr} \; , \qquad (3.6)$$

and

$$I_{cqs} = \omega\, C\, V_{ds} = -\, I_{qs} - I_{qr}$$
$$I_{cds} = -\,\omega\, C\, V_{qs} = -\, I_{ds} - I_{dr} \; . \qquad (3.7)$$

Substituting (3.3) into (3.6) and solving for the load currents gives

$$I_{qr} = \frac{V_{qs} R_L - \omega L V_{ds}}{R_L^2 + \omega^2 L^2}$$
$$I_{dr} = \frac{V_{qs} \omega L + R_L V_{ds}}{R_L^2 + \omega^2 L^2}. \tag{3.8}$$

Substituting the load current equations of (3.8) into (3.7) gives

$$V_{qs} = -\frac{(I_{qs} R_L^2 - I_{qs} \omega^2 L^2 - V_{qs} R_L)}{(L \omega - \omega C R_L^2 - \omega^3 L^2 C)}$$
$$V_{ds} = -\frac{(\omega C I_{qs} R_L^2 + \omega^3 C L^2 I_{qs} - I_{qs} \omega L + I_{ds} R_L)}{(\omega^4 L^2 C^2 - 2 \omega^2 C L + 1 + \omega^2 R_L^2)}. \tag{3.9}$$

It is worthwhile to note that the above voltage equations of (3.9) were obtained using only the load side parameters. Therefore, these voltage equations can be used to equate to the terminal voltage of any electric machine (or transmission line) no matter what type of generator machine is used.

Now, for the permanent magnet side, as stated previously

$$V_{qs} = r_s I_{qs} + \omega \lambda_e + \omega L_d I_{ds}$$
$$V_{ds} = r_s I_{ds} - \omega L_q I_{qs}. \tag{3.10}$$

Therefore,

$$-\frac{(I_{qs} R_L^2 - I_{qs}\,\omega^2 L^2 - V_{qs} R_L)}{(L\,\omega - \omega\, C\, R_L^2 - \omega^3 L^2 C)} = r_s I_{qs} + \omega\,\lambda_e + \omega\, L_d\, I_{ds}$$
$$-\frac{(\omega\, C\, I_{qs} R_L^2 + \omega^3 C\, L^2 I_{qs} - I_{qs}\,\omega\, L + I_{ds} R_L)}{(\omega^4 L^2 C^2 - 2\,\omega^2 C\, L + 1 + \omega^2 R_L^2)} = r_s I_{ds} - \omega\, L_q\, I_{qs} \;. \tag{3.11}$$

Manipulating (3.11) and solving for the currents gives

$$I_{qs} = \frac{n_{qq}1\, R_L^4 + n_{qq}2\, R_L^3 + n_{qq}3\, R_L^2 + n_{qq}4\, R_L + n_{qq}5}{d_d 1\, R_L^4 + d_d 2\, R_L^3 + d_d 3\, R_L^2 + d_d 4\, R_L + d_d 5}$$
$$I_{ds} = \frac{n_{dd}1\, R_L^4 + n_{dd}2\, R_L^2 + n_{dd}3}{d_d 1\, R_L^4 + d_d 2\, R_L^3 + d_d 3\, R_L^2 + d_d 4\, R_L + d_d 5} \;, \tag{3.12}$$

where

$$x_c = \omega\, C \;\;,\;\; x_l = \omega\, L \;\;,\;\; x_q = \omega\, L_q$$
$$x_d = \omega\, L_d \;\;,\;\; E = \omega\,\lambda_e$$

$$n_{dd}1 = E\,x_c^2(x_q\,x_c^2 - x_c)$$
$$n_{dd}2 = -E\,x_c^2\,x_l + E\,x_c$$
$$n_{dd}3 = E(x_c^2\,x_l^2 - 2\,x_c\,x_l + 1)(x_q\,x_c^2\,x_l^2 - 2\,x_q\,x_c\,x_l + x_q - x_c\,x_l^2 + x_l)$$
$$n_{qq}1 = r_s\,x_c^4\,E$$
$$n_{qq}2 = E\,x_c^2$$
$$n_{qq}3 = 2\,r_s\,x_c^4\,E\,x_l^2 - 4\,r_s\,x_c^3\,E\,x_l + 2\,r_s\,x_c^2\,E$$
$$n_{qq}4 = E\,x_c^2\,x_l^2 - 2\,E\,x_c\,x_l + E$$
$$n_{qq}5 = E(x_c^2\,x_l^2 - 2\,x_c\,x_l + 1)^2\,r_s$$
$$d_d1 = -r_s^2\,x_c^4 - x_d\,x_c^4\,x_q + x_d\,x_c^3 + x_q\,x_c^3 - x_c^2$$
$$d_d2 = -2\,r_s\,x_c^2$$
$$d_d3 = (-2\,r_s\,x_c^2\,x_l^2 + 4\,r_s\,x_c\,x_l - 2\,r_s)\,r_s\,x_c^2 + (x_d\,x_c^2\,x_l^2 + 2\,x_d\,x_c\,x_l)(x_q\,x_c^2 - x_c)$$
$$+(-x_d\,x_c^2 + x_c)(x_q\,x_c^2\,x_l^2 - 2\,x_q\,x_c\,x_l + x_q - x_c\,x_l^2 + x_l) - 1$$
$$d_d4 = -2\,r_s\,x_c^2\,x_l^2 + 4\,r_s^2\,x_c\,x_l - 2\,r_s$$
$$d_d5 = -(r_s^2)\,x_c^4\,x_l^4 + 4\,r_s^2\,x_c^3\,x_l^3 - 6\,r_s^2\,x_c^2\,x_l^2 + 4\,r_s^2\,x_c\,x_l - r_s^2$$
$$-x_d\,x_c^4\,x_l^4\,x_q + 4\,x_d\,x_c^3\,x_l^3\,x_q - 6\,x_d\,x_c^2\,x_l^2\,x_q + x_d\,x_c^3\,x_l^4$$
$$+\ 3\,x_d\,x_c^2\,x_l^3 + 4\,x_d\,x_c\,x_l\,x_q + 3\,x_d\,x_c\,x_l^2 - x_d\,x_q - x_d\,x_l + x_c^3\,x_l^4\,x_q$$
$$-2\,x_c^2\,x_l^3\,x_q + x_c\,x_l^2\,x_q - x_c^2\,x_l^4 + x_c\,x_l^3\ .$$

Now, the d and q axis currents can be combined using the following relationship:

$$I_s^2 = I_{qs}^2 + I_{ds}^2\ . \tag{3.13}$$

Substituting the values obtained in Equation (3.12) for I_{ds} and I_{qs} into Equation (3.13) and solving the equation in terms of the load resistance gives the eighth order term

$$A_o + \sum_{n=1}^{8} A_n\,R_L^n = 0\ , \tag{3.14}$$

Where

$$
\begin{aligned}
A_8 &= - n_{qq} 1^2 - n_{dd} 1^2 + I_s^2\, d_d\, 1^2 \\
A_7 &= 2\, I_s^2\, d_d\, 1\, d_d\, 2 - 2\, n_{qq}\, 1\, n_{qq}\, 2 \\
A_6 &= - 2\, n_{dd}\, 1\, n_{dd}\, 2 - 2\, n_{qq}\, 1\, n_{qq}\, 3 + 2\, I_s^2\, d_d\, 1\, d_d\, 3 + I_s^2\, d_d\, 2^2 - n_{qq}\, 2^2 \\
A_5 &= - 2\, n_{qq}\, 2\, n_{qq}\, 3 - 2\, n_{qq}\, 1\, n_{qq}\, 4 + 2\, I_s^2\, d_d\, 1\, d_d\, 4 + 2\, I_s^2\, d_d\, 2\, d_d\, 3 \\
A_4 &= - n_{dd}\, 2^2 - 2\, n_{qq}\, 2\, n_{qq}\, 4 + 2\, I_s^2\, d_d\, 1\, d_d\, 5 + 2\, I_s^2\, d_d\, 2\, d_d\, 4 \\
&\quad - 2\, n_{dd}\, 1\, n_{dd}\, 3 - 2\, n_{qq}\, 1\, n_{qq}\, 5 + I_s^2\, d_d\, 3^2 - n_{qq}\, 3^2 \\
A_3 &= - 2\, n_{qq}\, 3\, n_{qq}\, 4 + 2\, I_s^2\, d_d\, 2\, d_d\, 5 - 2\, n_{qq}\, 2\, n_{qq}\, 5 + 2\, I_s^2\, d_d\, 3\, d_d\, 4 \\
A_2 &= - 2\, n_{qq}\, 3\, n_{qq}\, 5 - 2\, n_{dd}\, 2\, n_{dd}\, 3 + I_s^2\, d_d\, 4^2 + 2\, I_s^2\, d_d\, 3\, d_d\, 5 - n_{qq}\, 4^2 \\
A_1 &= - 2\, n_{qq}\, 4\, n_{qq}\, 5 + 2\, I_s^2\, d_d\, 4\, d_d\, 5 \\
A_o &= - n_{qq}\, 5^2 + I_s^2\, d_d\, 5^2 - n_{dd}\, 3^2 \ .
\end{aligned}
$$

Equation (3.14) allows the system to be solved in closed form without using iterative techniques. The procedure involves first specifying a particular operating frequency, as well as the value of the capacitor and load inductance. Next, the stator current I_s is specified. With the current known, the IPM machine parameters L_q , L_d , and λ_e can be found using Equation (2.32). The roots of Equation (3.14) are then determined. The root which is positive and real is the appropriate value of R_L. The solution for the d and q axis currents can then be found using Equation (3.12). Next, the d and q axis voltages of the IPM can be found using Equation (3.9) or Equation (3.10). Either one should give the same solution and, therefore, comparing the two offers a useful check as to the accuracy of the calculation. The load voltages and currents can then be found using Equations (3.8), (3.3), and (3.5). The entire procedure can be repeated for stator current values ranging from near zero amperes up to a relatively high current.

3.3 Mathematical Model of IPM Feeding an R Load with Capacitive Compensation

The derivation for a purely resistive load with capacitive compensation is the same as that for a resistive and inductive load except that the inductive value L is equal to zero. The dq representation of the PM machine connected to resistive load with shunt capacitors at the terminals is given in Figure 3.3. The d and q terminal voltage equations can be written as When the voltage equations for the load are equated to the voltage equations of the PM

$$V_{qs} = -\frac{(I_{qs} R_L^2 - V_{qs} R_L)}{(-\omega C R_L^2)}$$
$$V_{ds} = -\frac{(\omega C I_{qs} R_L^2 + I_{ds} R_L)}{(1 + \omega^2 R_L^2)} \quad . \tag{3.15}$$

machine and the d and q currents are solved the result is

$$I_{qs} = \frac{r_q 3 R_L^2 + r_q 2 R_L + r_q 1}{d_r 3 R_L^2 + d_r 2 R_L + d_r 1}$$
$$I_{ds} = \frac{r_d 2 R_L^2 + r_d 1}{d_r 3 R_L^2 + d_r 2 R_L + d_r 1} \quad , \tag{3.16}$$

where

$$r_q 1 = -\omega \lambda_e r_s , \quad r_q 2 = -\omega \lambda_e , \quad r_q 3 = -\omega^3 \lambda_e r_s C^2$$
$$d_r 1 = r_s^2 + \omega L_d + \omega L_q , \quad d_r 2 = 2 r_s ,$$
$$d_r 3 = r_s^2 \omega^2 C^2 + \omega^4 L_d L_q C^2 - \omega^2 L_d C - \omega^2 C L_q + 1$$
$$r_d 1 = -\omega^2 \lambda_e L_q , \quad r_d 2 = -\omega^4 \lambda_e L_q C^2 - \omega^2 \lambda_e C .$$

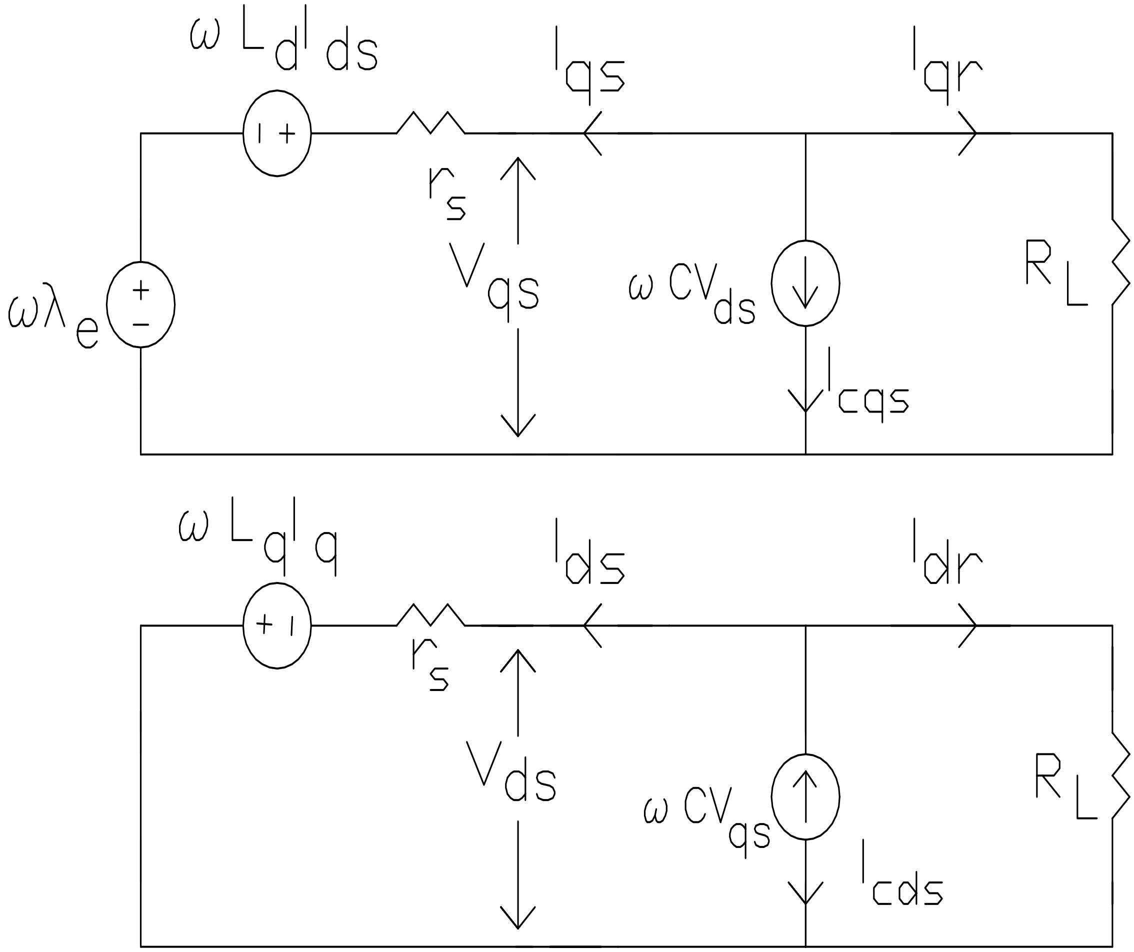


Figure 3.3. Equivalent circuit of dq representation of IPM machine connected to a resistive load with shunt capacitive compensation

The d-q current equations can now be substituted (as was done for the case of the RL load) into the current equation

$$I_s^2 - I_{qs}^2 - I_{ds}^2 = 0 \ . \qquad (3.17)$$

After substitution, and solving the equation in terms of the load resistance gives the fourth order equation

$$B_0 + \sum_{n=1}^{4} (B_n R_L^n) = 0 \qquad (3.18)$$

where

$$B_0 = r_d 1^2 - r_q 1^2 + I_s^2 d_r 1^2$$
$$B_1 = 2 I_s^2 d_r 2 d_r 1 - 2 r_q 2 r_q 1$$
$$B_2 = - 2 r_d 2 r_d 1 + 2 I_s^2 d_r 3 d_r 1 + I_s^2 d_r 2^2 - 2 r_q 3 r_q 1 - r_q 2^2$$
$$B_3 = 2 I_s^2 d_r 3 d_r 2 - 2 r_q 3 r_q 2$$
$$B_4 = - r_d 2^2 + I_s^2 d_r 3^2 - r_q 3^2$$

With the operating frequency and value of capacitance given, the load resistance can be solved for a particular stator current value.

3.4 Mathematical Model of IPM Feeding an R Load

The equivalent circuit of the PM machine feeding a purely resistive load is shown in Figure 3.4. The derivation for this system is quite easily accomplished by setting the capacitance equal to zero. With this done,

$$I_{qs} = \frac{s_q 2\, R_L + s_q 1}{e_r 3\, R_L^2 + e_r 2\, R_L + e_r 1}$$
$$I_{ds} = \frac{s_d 1}{e_r 3\, R_L^2 + e_r 2\, R_L + e_r 1} \quad , \tag{3.19}$$

where

$$s_q 1 = -\omega\, \lambda_e\, r_s\,, \quad s_q 2 = -\omega\, \lambda_e\,,$$
$$e_r 1 = r_s^2 + \omega\, L_d + \omega\, L_q\,, \quad e_r 2 = 2\, r_s\,, e_r 3 = 1$$
$$s_d 1 = -\omega^2\, \lambda_e\, L_q \quad .$$

The d and q axis currents can now be combined using the property

$$I_s^2 - I_{qs}^2 - I_{ds}^2 = 0 \quad , \tag{3.20}$$

which, after simplification gives the fourth order equation

$$C_0 + \sum_{n=1}^{4} (C_n\, R_L^n) = 0 \quad , \tag{3.21}$$

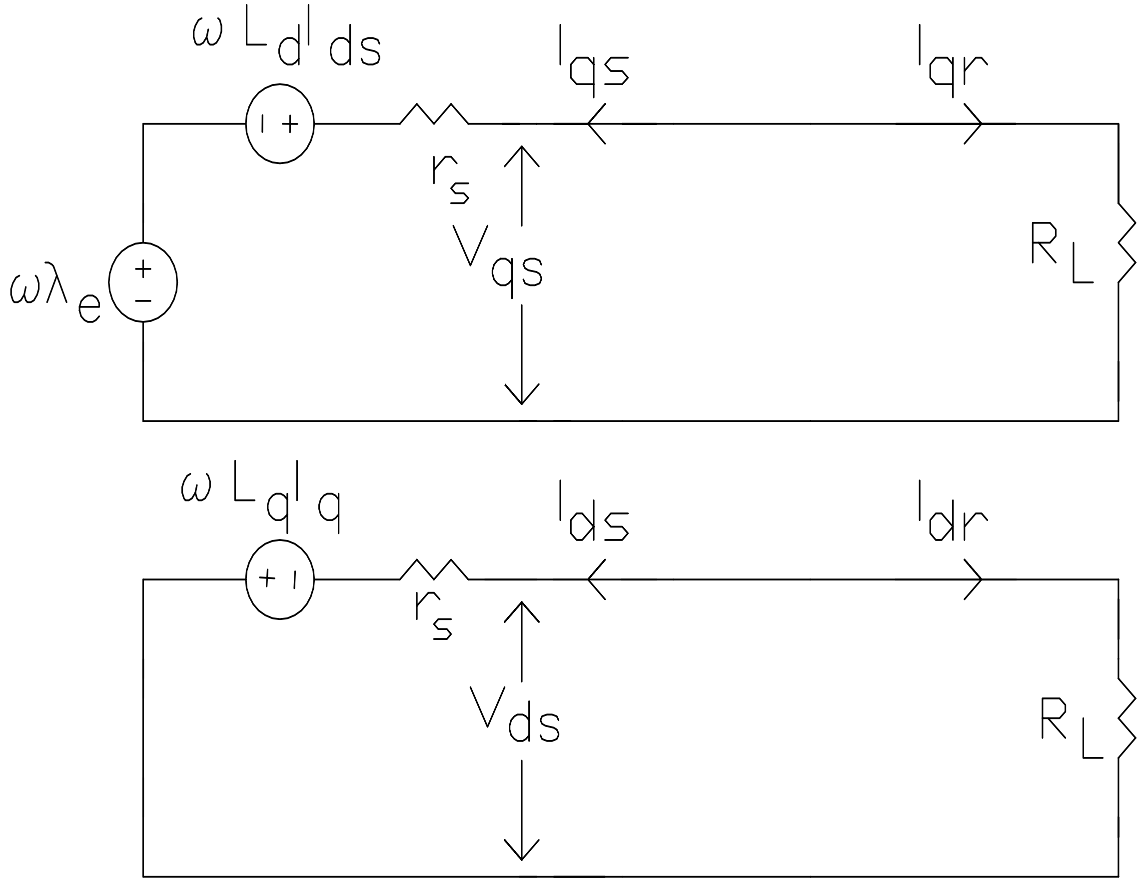


Figure 3.4. Equivalent circuit of IPM machine feeding a resistive load

where

$$
\begin{aligned}
C_0 &= s_d 1^2 - s_q 1^2 + I_s^2 e_r 1^2 \\
C_1 &= 2 I_s^2 e_r 2 e_r 1 - 2 s_q 2 s_q 1 \\
C_2 &= - 2 s_d 2 s_d 1 + 2 I_s^2 e_r 3 e_r 1 + I_s^2 e_r 2^2 - s_q 2^2 \\
C_3 &= 2 I_s^2 e_r 3 e_r 2 \\
C_4 &= I_s^2 e_r 3^2 \ .
\end{aligned}
$$

It is interesting to note that Equation (3.21) can actually be reduced to a second order term by noticing that, since the load and stator resistances are in series, the load resistance and the stator resistance can be combined to form a resistance called R_{LT}. If the load resistance R_L is replaced by the term R_{LT} and, since the stator resistance is contained in the term R_{LT} , r_s is set equal to zero, then the terms C_1 and C_3 become equal to zero . The solution can then be written as

$$R_{LT}^4 C_4 + R_{LT}^2 C_2 + C_0 = 0 \ , \tag{3.22}$$

and the solution R^2_{LT} can be solved as a simple quadratic equation. Taking the square root of this solution gives R_{LT}, and, with r_s already known, R_L can be found by subtracting the stator resistance from R_{LT}.

3.5 Comparison of Experimental Results with Calculations

Experimental results were obtained by driving the IPM machine at various frequencies and measuring the voltages and currents. Since the IPM used is a 4 pole machine, then the shaft speed to obtain, for example, a 60 Hz electrical output is 1800 rpm. The motor which was driving the IPM, a 5 hp induction 2 poles machine, was electrically driven by an adjustable speed drive. Since the induction machine was much larger than the IPM, it was assumed that the slip was negligible, and the speed of the shaft was directly proportional to the frequency of the drive.

3.5.1 IPM Feeding an R Load

A balanced 3 phase Y connected resistive load is varied from a high resistive value to a low resistive value and the power, line voltages, and line currents are measured. This procedure is repeated for a number of generator frequencies. The isolated IPM generator used in these experiments is stable beyond the maximum power point and the curves are shown to display the trend of the system. It should be noted however that operation beyond the maximum power point is not of much practical use since the efficiency is low, the voltage drops precipitously, and the currents become very large.

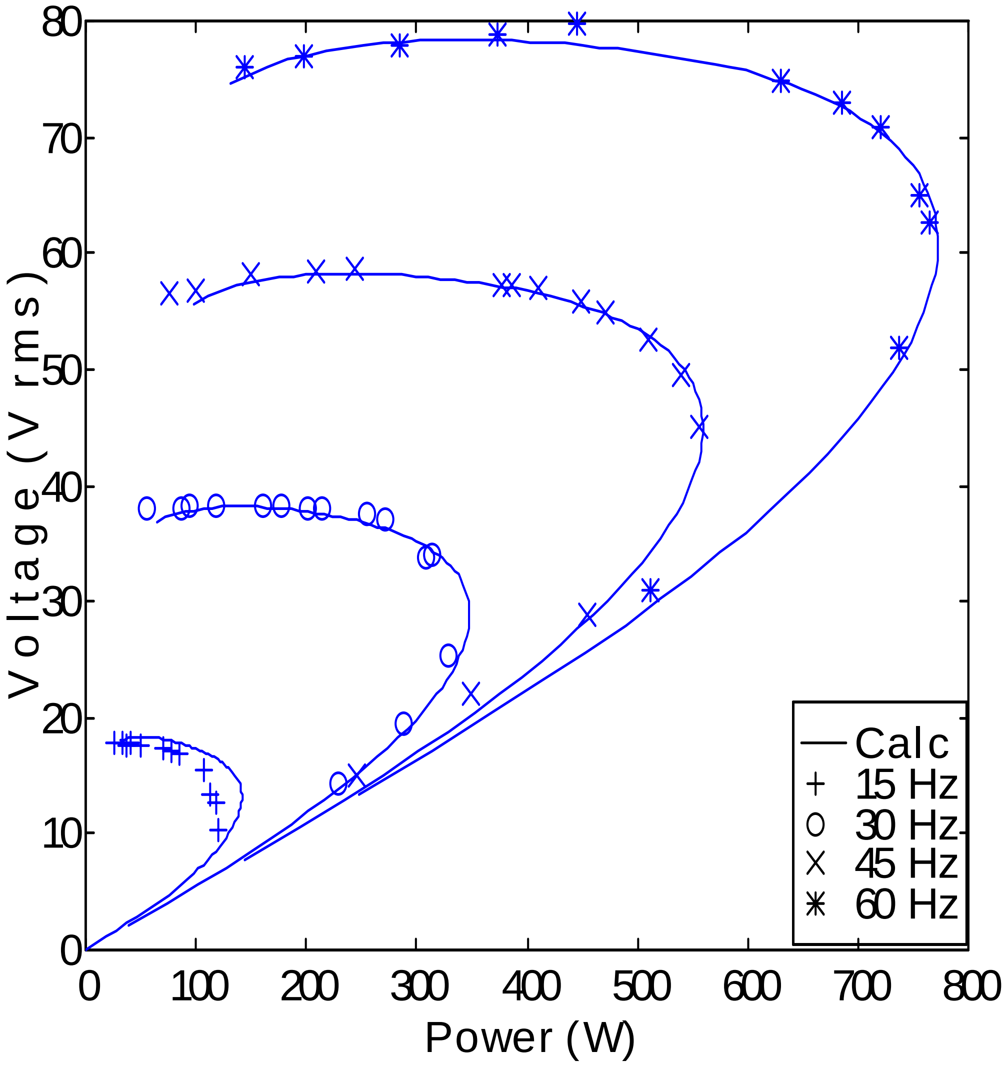


Figure 3.5. Measured and calculated line to neutral generator voltage vs load power output for various generator frequencies

Figure 3.5 shows the plot of the line to neutral terminal voltage vs the output power for four different frequencies. It can be seen that, up to the maximum power point, the voltage changes very little. In addition, there is actually negative voltage regulation for about half of the top part of the curve. It can be seen from Figure 3.5 that the maximum power point at 60 Hz for the case when no capacitor compensation is used is 800 watts.

Figure 3.6 shows the experimental and calculated results of the line current vs the output power. The lower part of the curves (where the current is low) is where one would ideally like to operate the machine. It is interesting to note that the maximum power point occurs around 4.1 amperes regardless of the operating frequency. This knowledge would be useful to have if a control or protection device scheme were implemented with the system.

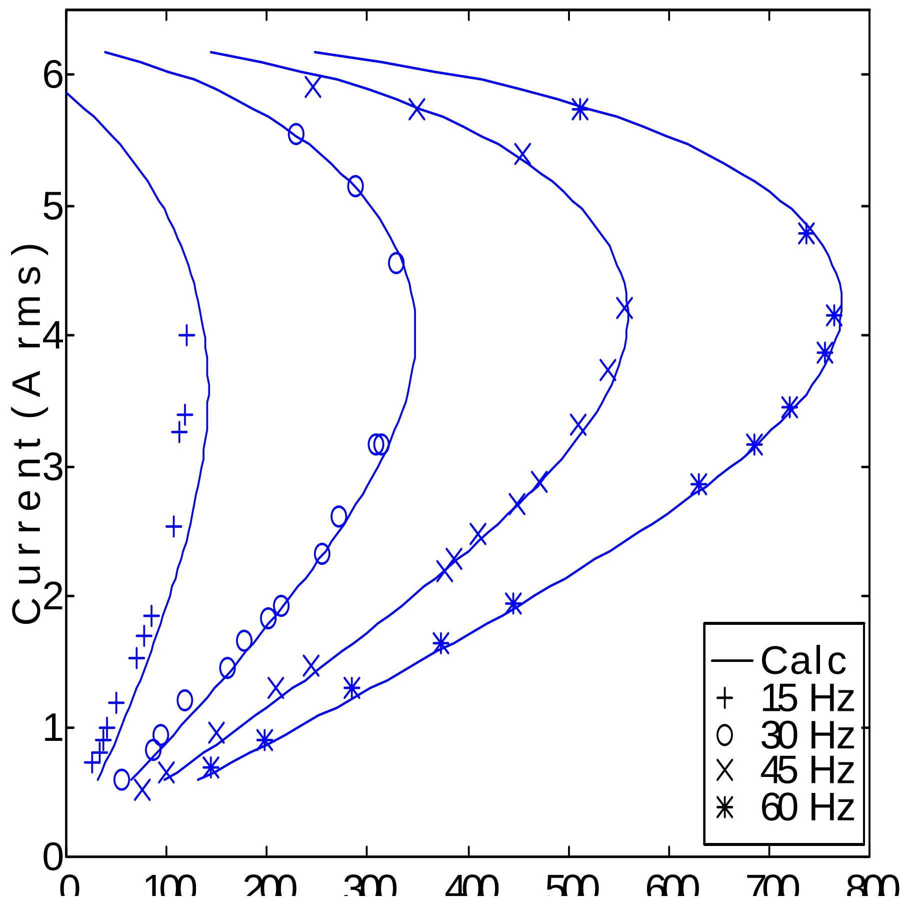


Figure 3.6. Measured and calculated generator line current vs output power for various frequencies

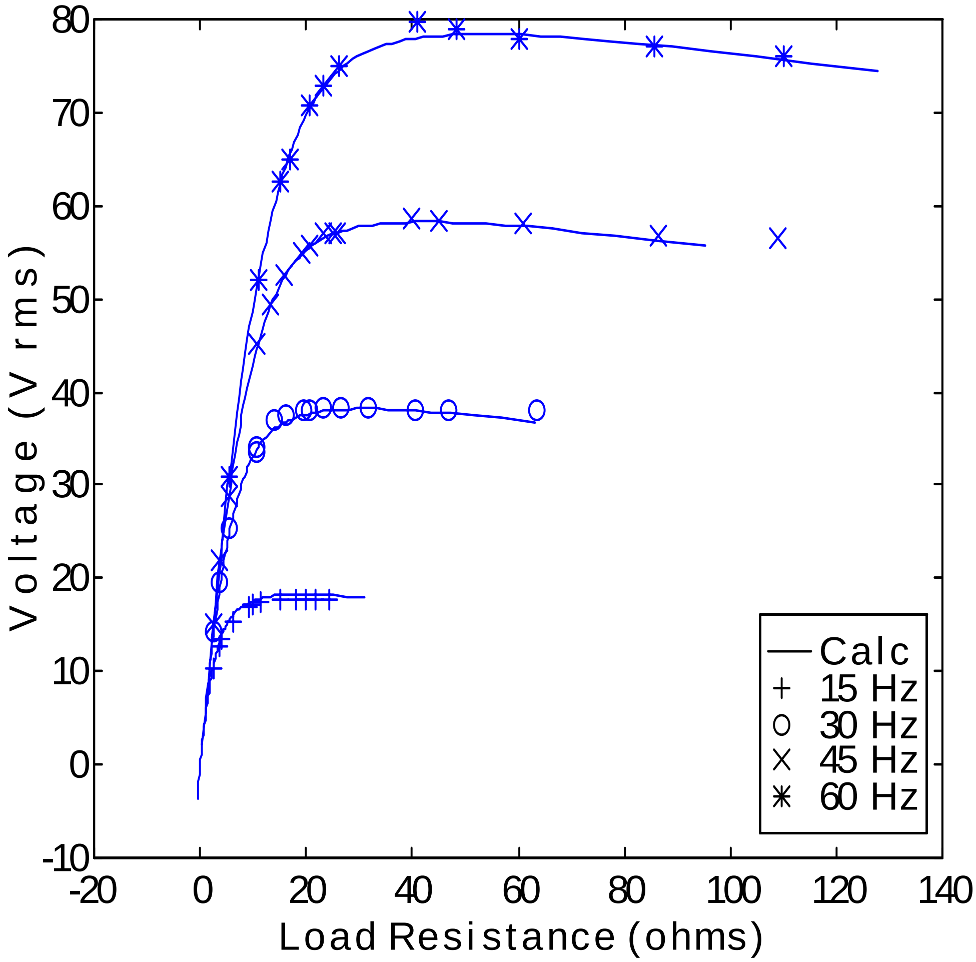


Figure 3.7. Measured and calculated load voltage vs load resistance

Figure 3.7 displays how the line to neutral voltage varies as the load resistance is changed. It can be seen that the voltage decay follows the same trajectory regardless of the operating frequency. Another point to be made is that the line to neutral voltage is relatively small. For example, at 60 Hz, one would normally like to have an rms voltage of approximately 120 volts since this is close to the voltage at which most small appliances, motors, and lights are designed.

The plot of Figure 3.8 shows how the output power of the system changes as the load resistance changes. It can be seen from the figure that there is a narrow band of load resistance values in which relatively large powers occur for each operating frequency. It can also be seen that the decay in power, caused by the precipitous fall of voltage for small resistance values also follows the same trajectory, regardless of the operating frequency.

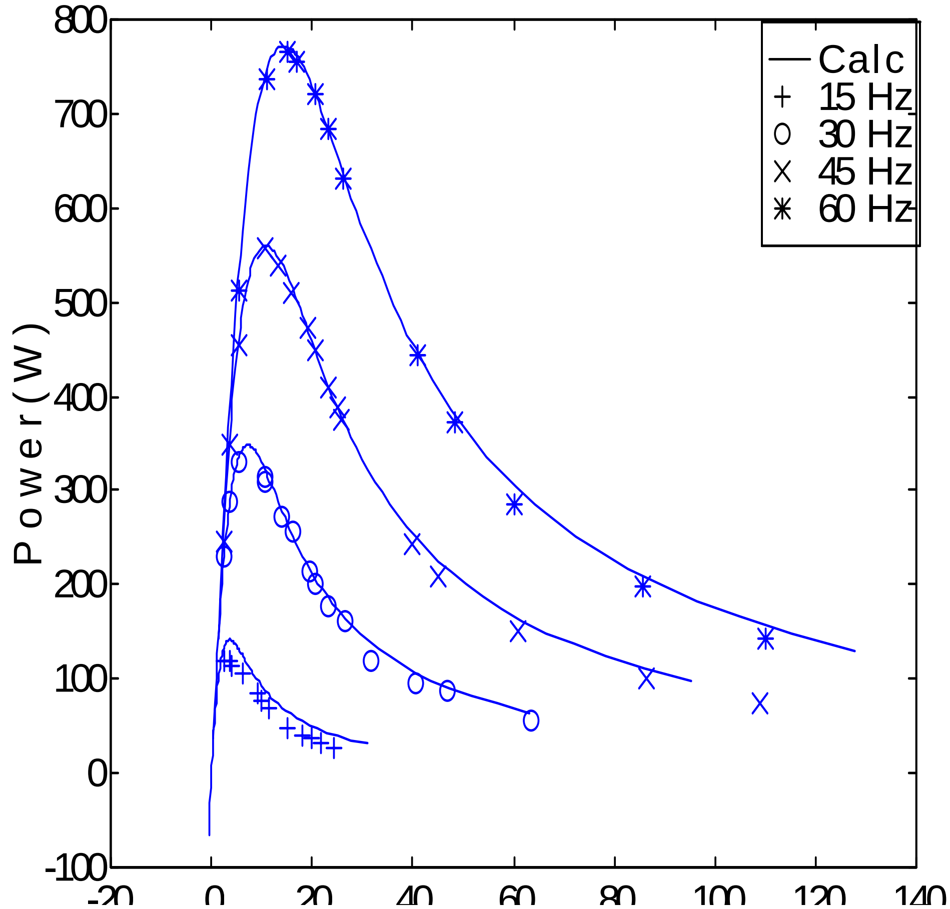


Figure 3.8. Measured and calculated output power vs load resistance for various frequencies

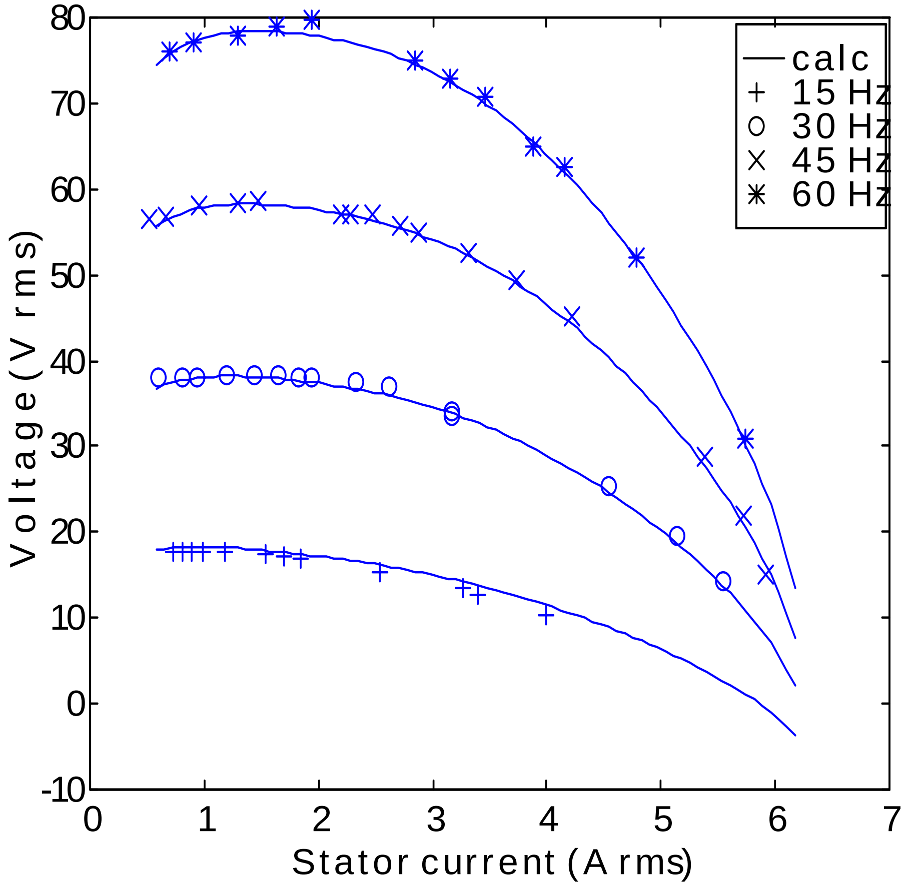


Figure 3.9. Measured and calculated line to neutral generator voltage vs stator current for various frequencies

Figure 3.9 displays how the line to neutral voltage and the line current vary. In a sense, the voltage of the machine is a function of the output current since the magnitude of the current output affects the parameters of the machine which in turn determines the performance. The operation of this machine is relatively "safe" in this generator mode for this configuration since, as can be seen by Figure 3.9, even when the voltage is near zero; the currents are still below 6.5 amperes rms. The current rating of the IPM is 5.3 amperes.

3.5.2 IPM Feeding an R Load With Shunt Capacitor Compensation

The graph shown in Figure 3.10 plots the line to neutral voltage of the IPM vs the output power of the generator when a 30 μF in Y connection is connected at the terminals of the machine. Although the trend is the same as the plots shown in Figure 3.5, it can be seen that the voltage at 60 Hz for the capacitor case is almost 30 volts higher than when no

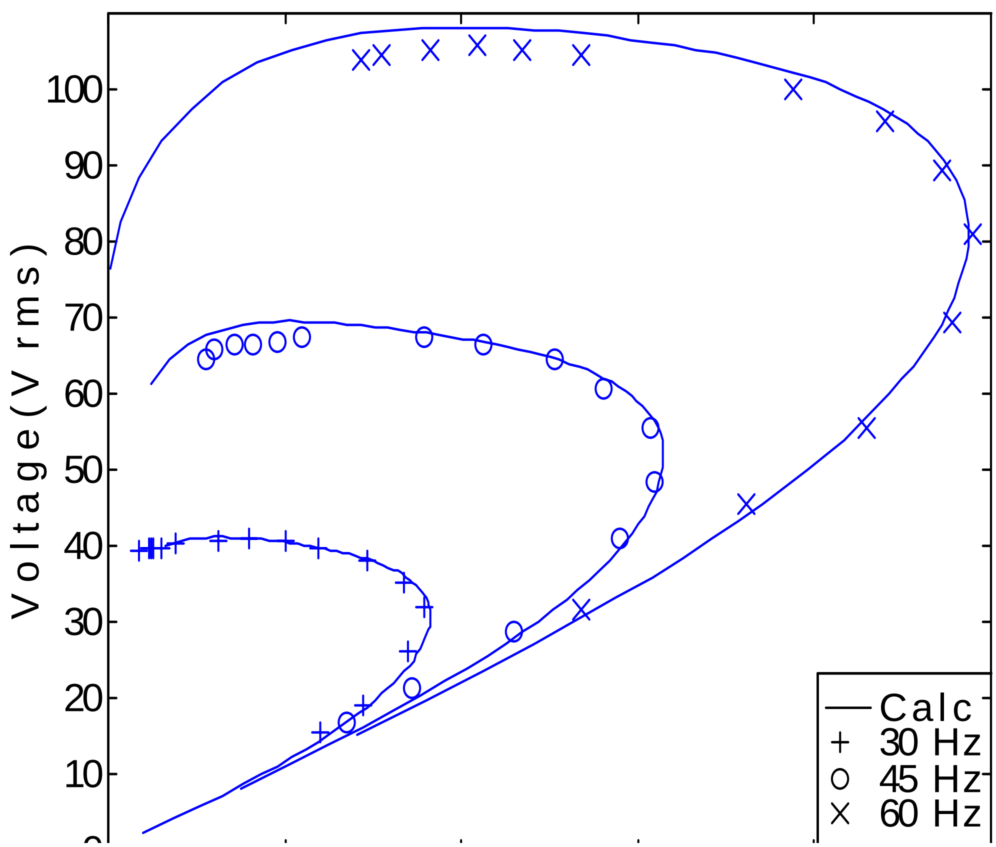


Figure 3.10. Measured and calculated line to neutral generator voltage vs output power for PM machine with capacitor compensation

capacitor is used. In addition, there is an increase in power output of the machine of approximately 200 watts for the 60 Hz case. The increase in power and voltage is due to the capacitors providing reactive power to the IPM.

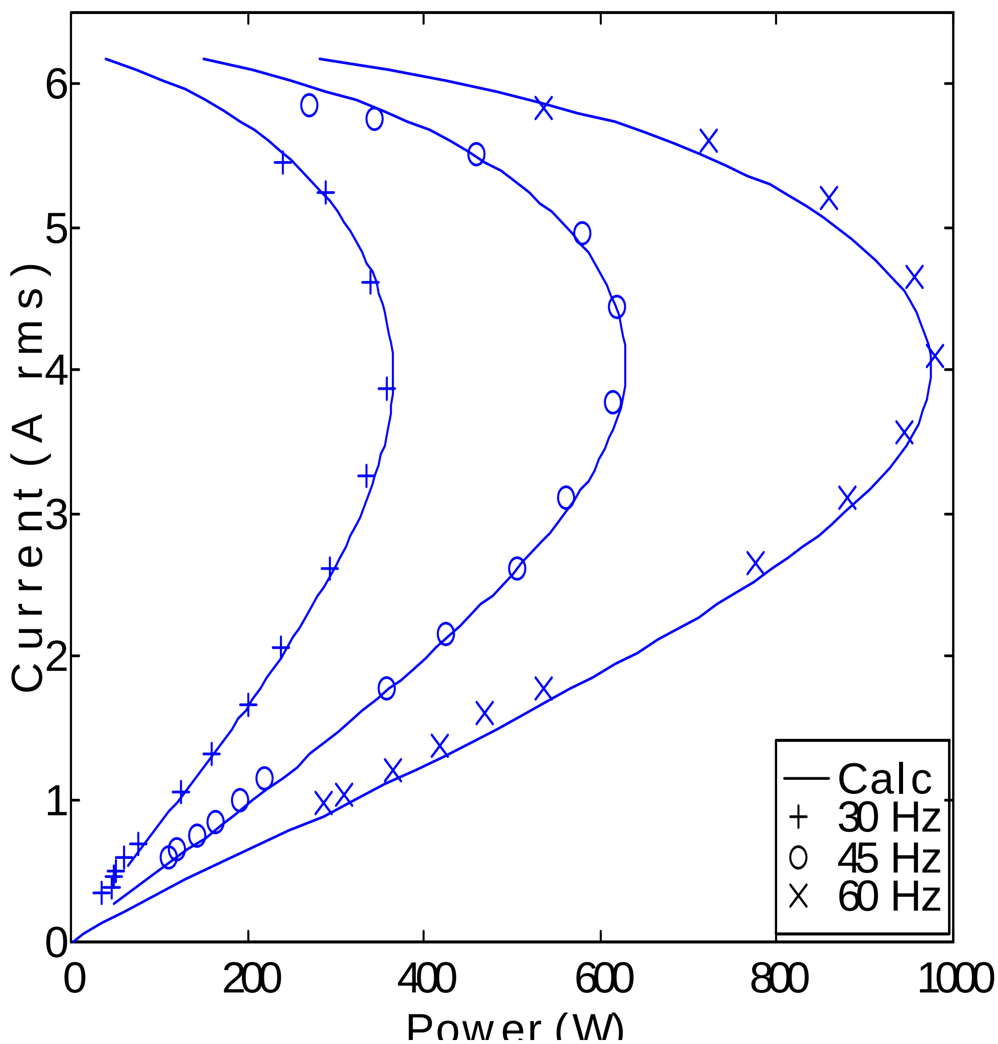


Figure 3.11. Measured and calculated generator line current vs output power for PM machine with capacitor compensation

The plots shown in Figure 3.11 show the current of the IPM vs the output power. As was the case when no shunt capacitors were used (see Figure 3.6) it can be seen that the maximum power point occurs when the line current is approximately 4.1 amperes regardless of the operating frequency.

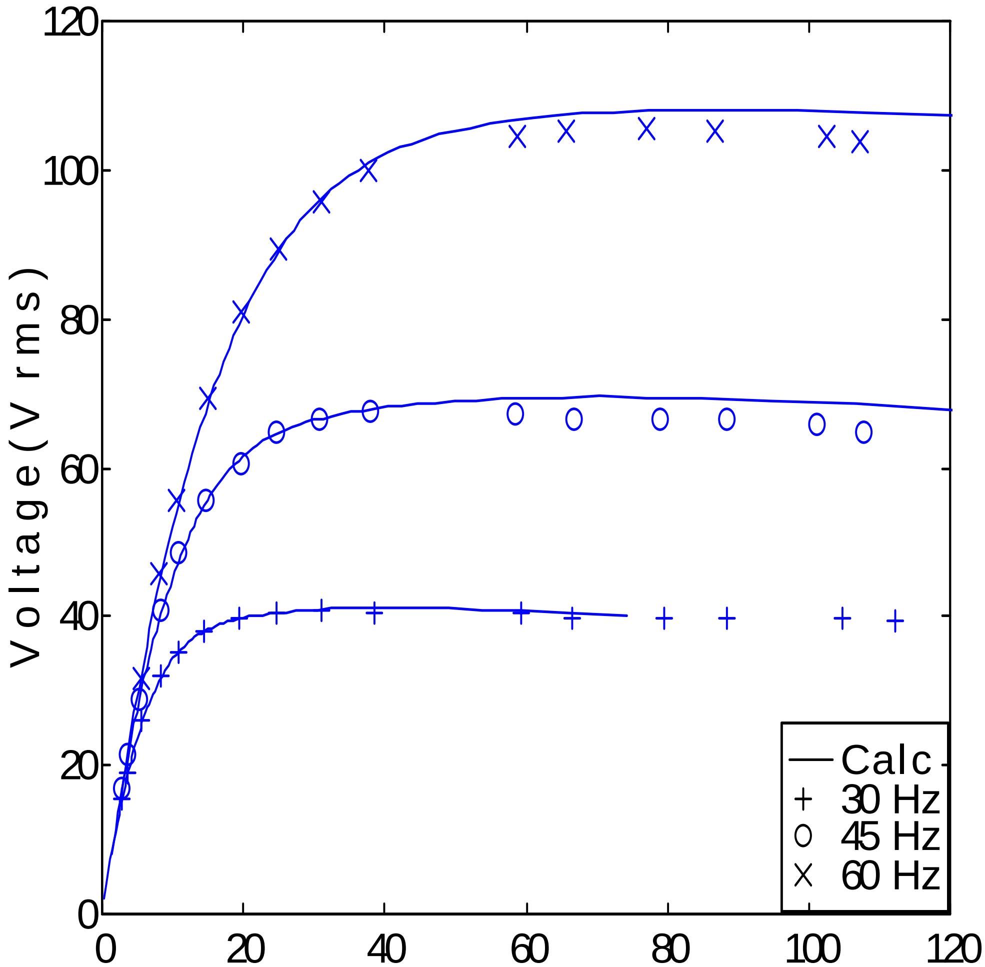


Figure 3.12. Measured and calculated line to neutral generator voltage vs per phase load resistance for shunt capacitor scheme

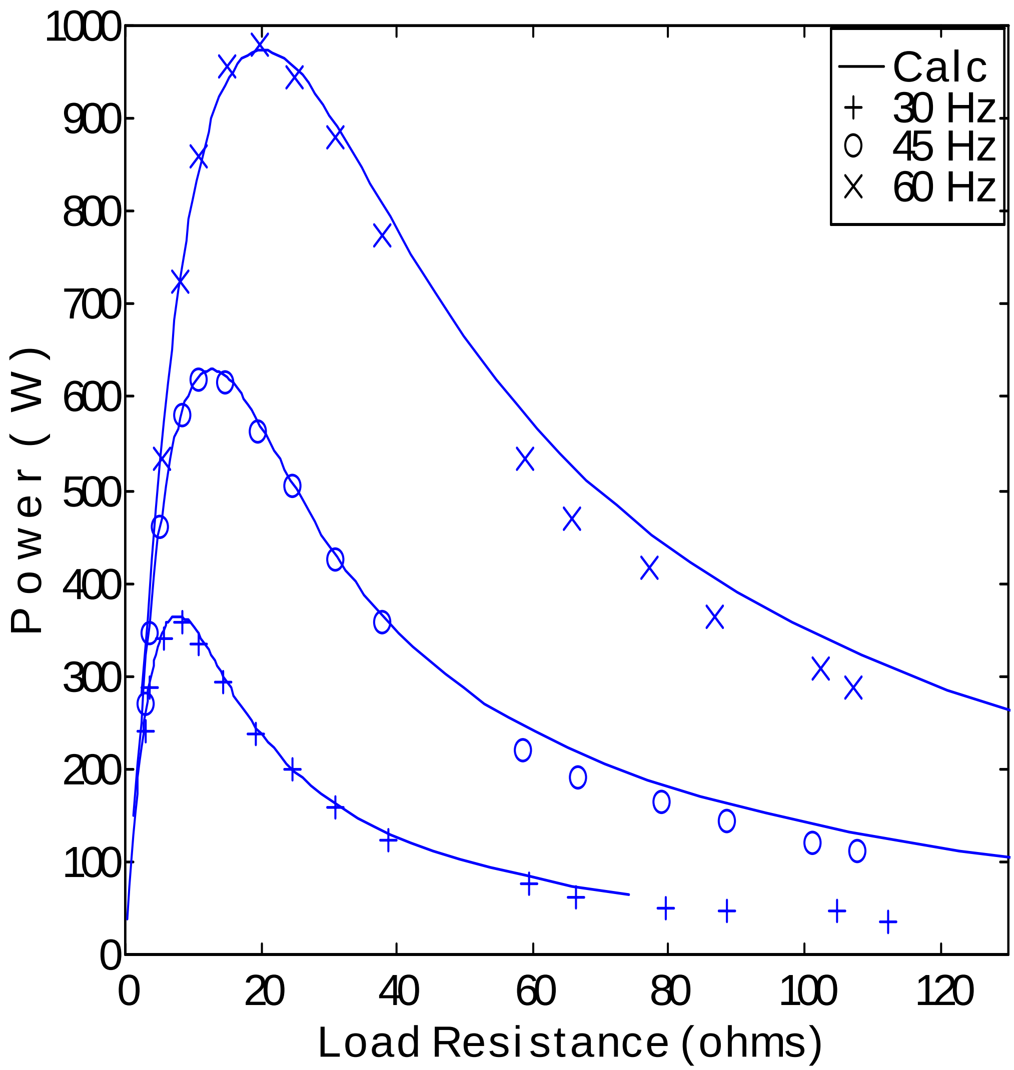


Figure 3.13. Measured and calculated output power vs load resistance for capacitor compensation scheme

Figures 3.12 and 3.13 display how the line to neutral voltage and the power into the load vary as the load resistance changes. The trends are exactly the same as those shown in Figures 3.7 and 3.8 (as one would expect) except for the fact that the magnitudes of both the line voltage and the output power have increased.

Finally, Figure 3.14 plots the line to neutral voltage vs the line current. Again, as was the case when no shunt capacitors were used, even for very low voltages, the currents are below 6.5 amperes rms. Thus, the use of capacitors in the system did not increase the current drawn from the machine when the voltage is very small.

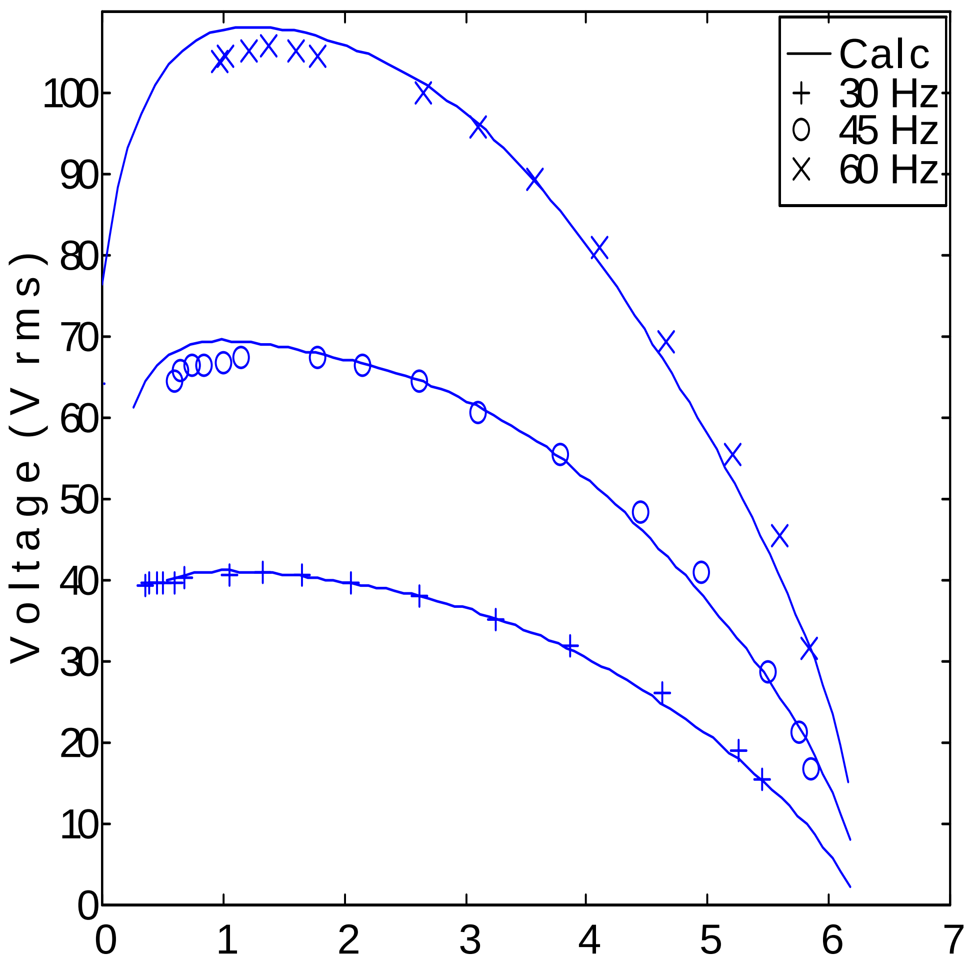


Figure 3.14. Measured and calculated stator current vs line to neutral generator voltage for capacitor compensation scheme

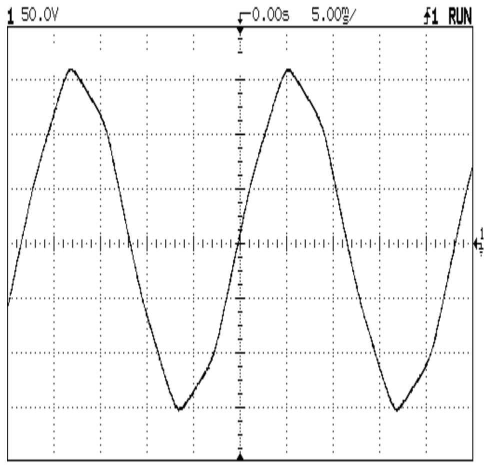
3.6 Comparison of Measured and Simulated Waveforms of IPM Machine with Shunt Capacitive Compensation Feeding a Resistive Load

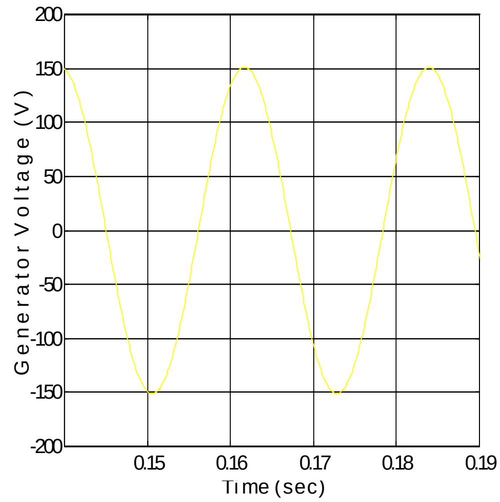
This section includes the comparison between simulation and measured waveforms for the IPM generator feeding a resistive load. Shunt capacitors are used at the terminals of the generator to increase the power output and terminal voltage. Two cases will be looked at. The first is when the resistive load is such that high power is produced at the load, and the second is when the resistive load is very high and little power flows in the load.

3.6.1 IPM Generator Feeding a Small Resistive Load

This section looks at measured and simulated waveforms when the IPM is operating at near its maximum power output point. All of the waveforms in this and the next section are at the frequency of a 45 Hz. Since the IPM is a 4 pole machine, then this means that the shaft speed is 1350 rpm. The load resistance for the waveforms presented in this section is 22 Ω.

Figure 3.15 shows the simulated and measured line to line voltage waveforms for the 22 Ω load. The waveforms are fairly close with the peak voltage of the measured value being only slightly higher than the peak of the simulated waveform.



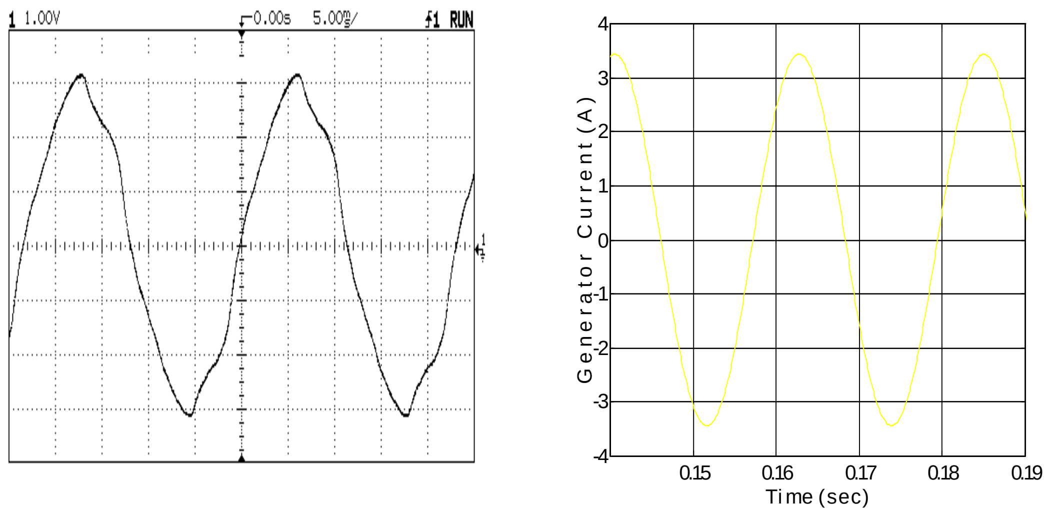


I. Measurement II. Simulation

Figure 3.15. Measured and simulated line to line voltage waveforms for the generator feeding a 22 Ω resistive load. Rotor speed=1350 rpm. Measured waveform scale: voltage: 50v/div, time 5ms/div

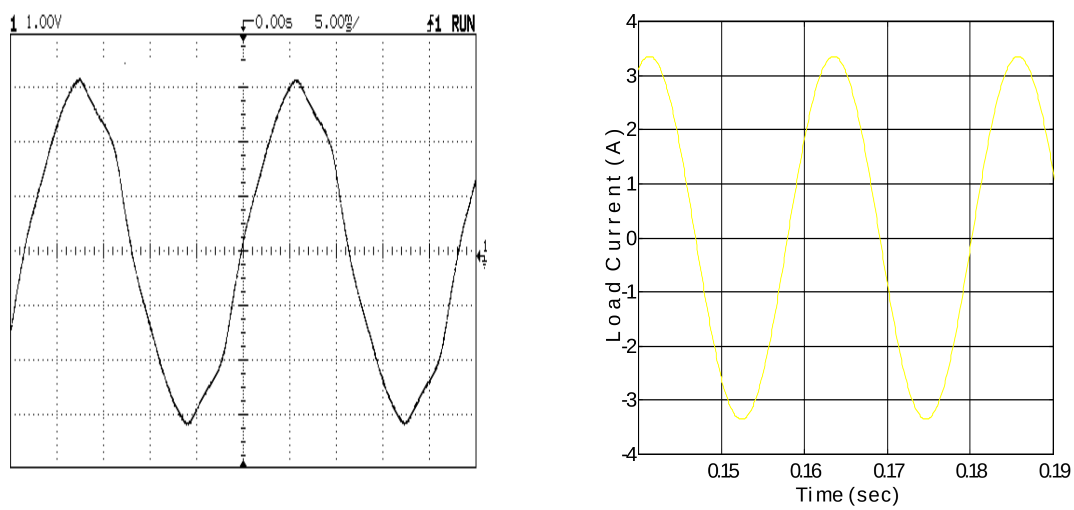
Figure 3.16 shows the measured and simulated waveforms of the generator current. Like the measured voltage waveform, it can be seen that the generator current waveform is not perfectly sinusoidal (whereas the simulated waveforms of both the current and voltage are sinusoidal) . Nevertheless, the magnitudes of the measured and simulated generator currents are reasonably close for this operating condition.

The measured and simulated waveforms of the current flowing into the load are shown in Figure 3.17. Again, the measured waveform shows a slight distortion, but the simulated and measured waveforms are reasonably close.



I. Measurement II. Simulation

Figure 3.16. Measured and simulated generator currents waveforms for a 22 Ω load. Rotor speed=1350 rpm. Measured waveform scale: current: 1A/div, time 5ms/div

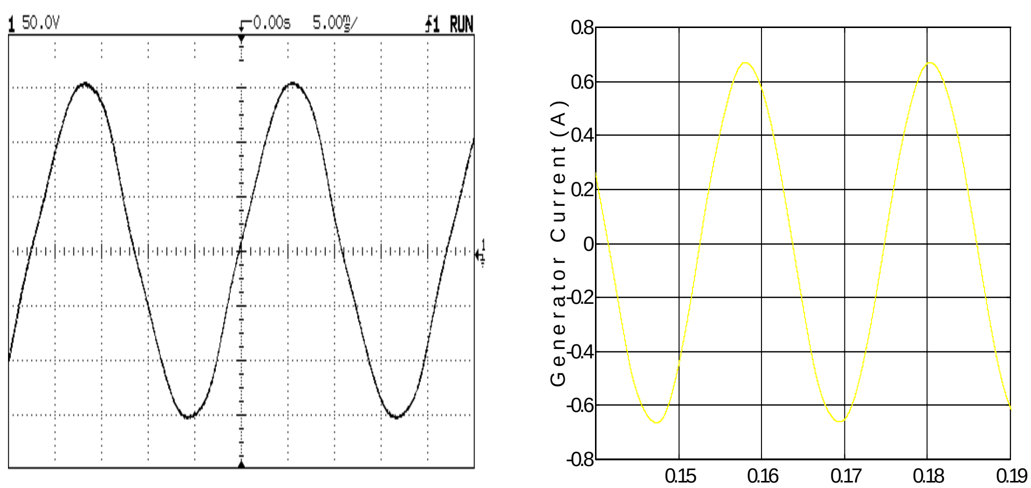


I. Measured II. Simulation

Figure 3.17. Measured and simulated load currents for a 22 Ω load. Rotor speed=1350 rpm. Measured waveform scale: current: 1A/div, time 5ms/div

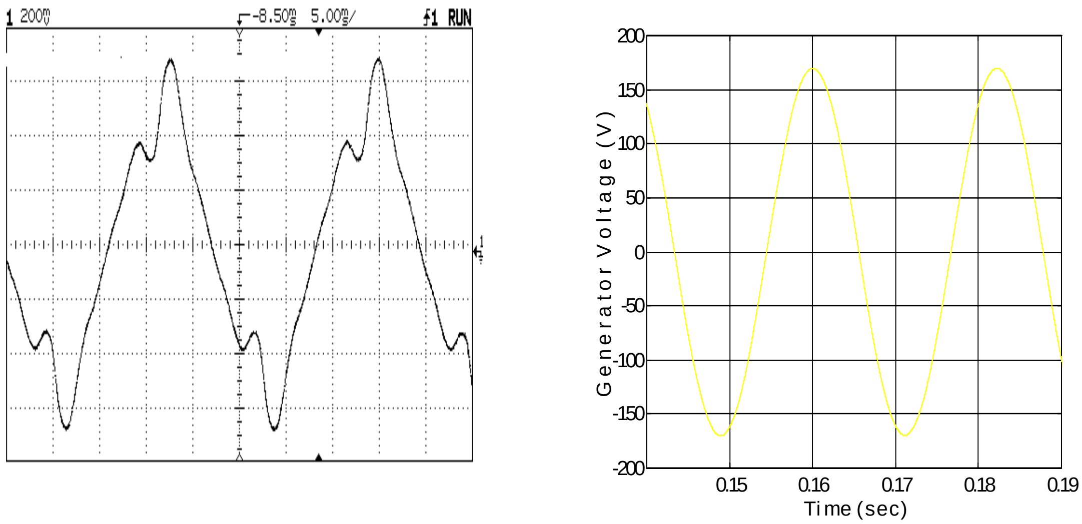
3.6.2 IPM Generator Feeding a Large Resistive Load

In this section, measured and simulated waveforms for the condition of a 205 Ω per phase load are described. The operating frequency is 45 Hz and the shunt capacitors are Y-connected 30 μF. Figures 3.18-3.20 display the measured and simulated waveforms of the line to line voltage, the generator current, and the load current. It is interesting to note that, while the measured line to line voltage of Figure 3.18 appears to be slightly less distorted than the voltage waveform for the heavy load condition (see Figure 3.15), the generator current waveform of Figure 3.19 has become very distorted. It can be seen in Figure 3.20 that the load current is much less distorted than the generator current and, thus, it can be inferred from this that the shunt capacitors are serving as a filter.



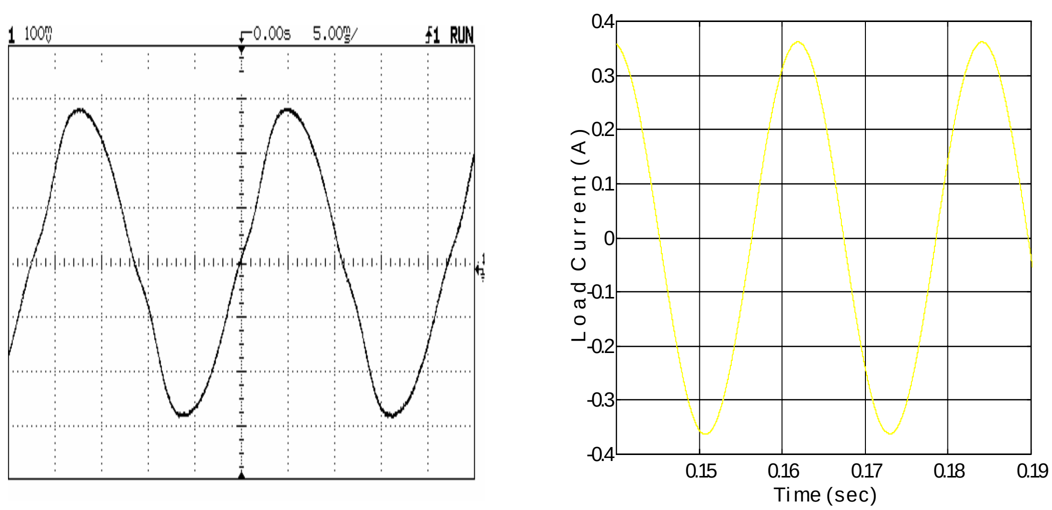
I. Measurement II. Simulation

Figure 3.18. Measured and simulated waveforms of the line to line voltage for a 205Ω load. Rotor speed = 1350 rpm. Measured waveform scale: voltage: 50V/div, time 5ms/div



I. Measurement II. Simulation

Figure 3.19. Measured and simulated waveforms of generator current for a 205Ω load. Rotor speed=1350 rpm. Measured waveform scale: current 200 mA/div, time 5ms/div



I. Measurement II. Simulation

Figure 3.20. Measured and simulated waveforms of load current for a 205Ω load. Rotor speed=1350 rpm. Measured waveform scale: current: 100 mA/div, time 5ms/div